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Rician Channel Modeling for Multi-probe Anechoic Chamber Setups

Wei Fan, Pekka Kyösti, Lassi Hentilä, Jesper Ø. Nielsen, and Gert F. Pedersen

Abstract—This paper discusses over the air (OTA) testing for multiple input multiple output (MIMO) capable terminals, with emphasis on modeling Rician channel models in the multi-probe anechoic chamber setups. A technique to model Rician channels is proposed. The line-of-sight (LOS) component, with an arbitrary polarization and an arbitrary impinging direction, and non-LOS (NLOS) component, with any impinging power angular spectrum (PAS), can be created. Simulation results show that the emulated Rician channels approximate the target models accurately in terms of field envelope distribution, K factor, Doppler spectrum and spatial correlation at the receiver (Rx) side.

Index Terms—MIMO OTA testing, multi-probe, anechoic chamber, Rician channel modeling, K factor estimation

I. INTRODUCTION

Over the air (OTA) testing of multiple-input multiple-output (MIMO) capable terminals has been actively discussed in standardization recently [1]. Due to its capability to physically synthesize radio propagation environments in a shielded laboratory, the multi-probe anechoic chamber method has attracted great research attention. The radio propagation environment, which is a key factor for MIMO performance, is reproduced as it would be experienced by the device under test (DUT) in the field environment.

As the testing is performed in a shielded anechoic chamber, the reproduced field in the lab is controllable and repeatable. The major challenge with the multi-probe method is to create a realistic multipath environment. Several papers have addressed channel modeling in multi-probe setups, where the goal is to reproduce 2D channel models with accurate spatial characteristics at the receiver (Rx) side, see e.g. [2]. Reference [3] extended the channel emulation technique for 3D channel models with 3D multi-probe setups. However, the work in the literature is limited to model the Rayleigh fading channel models so far. The discussions on channel models in MIMO OTA standards are limited to Rayleigh fading channel models as well [1], e.g. the SCME channel models. However, as shown in numerous contributions in the literature, the Rayleigh fading channel model is not generally valid. Often a specular path exists between the transmitter (Tx) and the Rx. The time varying envelope of the received signal in the multipath environment is often modeled by a Rician distribution, characterized by the K factor [4]. Furthermore,

Rician scenarios are expected to be more likely, as future cell sizes will further decrease. To test MIMO capable terminals in realistic environments in the lab, there is a strong need to model Rician channel models in the multi-probe setups.

Very few contributions have addressed modeling Rician fading channels in the multi-probe setups in the literature. An algorithm to model Rician fading models has been implemented in a commercial channel emulator, the Anite Propsim channel emulator. However, a description of the implemented algorithm is not available. In [2], it was briefly mentioned that the prefaded signal synthesis (PFS) technique can support emulating the Rician channel models with the line of sight (LOS) component limited to the directions where one of the probes is located. However, no details were given on how to model Rician fading channels and no results were given. In this paper, a novel technique is proposed to model the Rician fading channel models in the multi-probe setup, where the LOS path with an arbitrary incident direction is possible and a non-LOS (NLOS) component with arbitrary power angular spectrum (PAS) shape can be modeled. More specifically, the specular path is modeled using the so-called plane wave synthesis (PWS) technique, while the scattering NLOS component can be modeled with the PFS technique.

The main contributions of this paper lie in two aspects:

- A technique to create Rician channel models in the multi-probe anechoic chamber setups is proposed.
- A detailed analysis on the reproduced Rician channel models in the multi-probe setup is given, e.g. field envelope distribution, K factor estimation, spatial correlation, Doppler power spectrum, etc. Simulation results have shown that the reproduced Rician channels match very well with the target models.

II. METHOD

The Rician channel can be decomposed into a specular component for the LOS path and a scattering component for the NLOS path between the Tx and the Rx, where the Rician K -factor is defined as the power ratio of the two. In this section, the multi-probe anechoic chamber setup is first illustrated. After that the target channel models and the techniques to approximate the Rician channel models in the multi-probe setups are detailed.

A. Multi-probe setup and problem statement

An illustration of the multi-probe based anechoic chamber setup is shown in Figure 1. Probe antennas placed around

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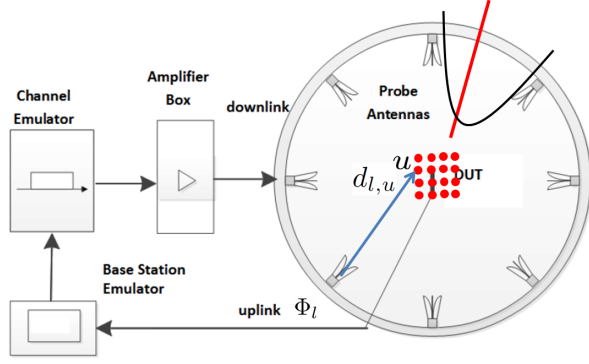


Figure 1. An illustration of the multi-probe based anechoic chamber setup. The red line illustrates the LOS specular component, while the black curve represents the NLOS scattering components. The red dots illustrate the potential locations for the Rx antenna.

the DUT are used as the transmitting antennas to create the multipath channels, with the help of channel emulators.

The LOS path can arrive at the receiver with arbitrary incoming direction. The NLOS scattering multipaths are often modelled by clusters, based on extensive measurements in various scenarios [5]. Typically a cluster consists of a number of rays and has a specifically shaped PAS. Several PAS models have been proposed, see e.g., the truncated Laplacian shape in [5]. It is desirable to enable emulation of Rician channels with an arbitrary impinging direction of the specular LOS components and an arbitrary PAS shape for the NLOS scattering component. An illustration of a target Rician channel model is shown in Figure 1.

The key of the channel emulation in the multi-probe setup is to ensure that the signals emitted from the probes are properly controlled such that the emulated channel seen by the DUT approximate the target channel model.

B. Target channel models

The channel models investigated in this study are geometry-based stochastic channel models (GSCMs), as they are adopted in the MIMO OTA standards [1]. The widely accepted MIMO channel models like SCME, WINNER, and IMT-Advanced models belong to this family [5]. For Tx array with an S elements and an Rx array with U elements, the channel coefficients for one of N multipath components are given by a $U \times S$ matrix of complex amplitudes. The wideband MIMO matrix \mathbf{H} can be written as:

$$\mathbf{H}(t) = \sqrt{\frac{K}{1+K}} \mathbf{H}_{los}(t) + \sqrt{\frac{1}{1+K}} \mathbf{H}_{nlos}(t), \quad (1)$$

where $\mathbf{H}(t) = \{h_{u,s,n}(t)\} \in \mathbb{C}^{U \times S \times N}$. is the instantaneous channel matrix. A detailed description of the channel coefficients can be found in [5]. Note that when Rician K factor approaches infinity, the matrix corresponds to the case of a pure LOS matrix and when $K = 0$, it becomes pure Rayleigh fading matrix. The discussion in this work is limited to single polarized 2D channel models for the sake of simplicity. Note that arbitrarily polarized LOS path can be easily created by

synthesizing the horizontally polarized and vertically polarized components independently, with their amplitudes and phases determined by the target arbitrarily polarized field.

1) *LOS component*: The LOS component can be represented by a time-variant plane wave, with arbitrary impinging direction. The time-evolution of the LOS path is determined by its Doppler frequency, as detailed in [5]. Basically, the parameters of the LOS component include the Tx and Rx antenna array, angle of departure (AoD) and angle of arrival (AoA) for the LOS component, Doppler frequency and delay.

2) *NLOS component*: The NLOS component consists of one or several clusters, and each cluster is composed by a number of rays. The channel coefficients for the NLOS component are given by the ray based models, as detailed in [5]. For each ray, the AoD/AoA, amplitude, random initial phase and Doppler frequency is defined. The PAS of the cluster is defined by the AoAs/AoDs and magnitudes of the rays within the cluster.

C. Emulated channel models

The emulation of the LOS and NLOS components is described separately below.

1) *LOS component*: For the LOS component, the goal is to approximate a time-evolving plane wave with an arbitrary impinging direction inside the test area.

As explained in [2], [6], we can approximate a static plane wave with an arbitrary incident direction to the test area, by selecting appropriate complex weights for the probes. Several techniques have been proposed in the literature to obtain the optimal complex weights, see e.g. the optimization methods in [2], [3], the interpolation technique in [6] and the spherical wave expansion technique in [7].

Assuming a uniform probe configuration, the following complex probe weights will create a static plane wave with angle θ [6],

$$g_i = \frac{1}{L} \sum_{l=1}^L \cos[\epsilon \cdot (\theta - \Phi_i)], \quad i = 1, \dots, L \quad (2)$$

where g_i is the weight corresponding to the i th probe with $\epsilon = l - \lceil \frac{L}{2} \rceil$, where $\lceil \cdot \rceil$ is the ceiling operator which rounds up the number inside the bracket to the next higher integer. L is the number of OTA probes and Φ_l is the fixed angle of the l th probe.

Introducing a Doppler shift, a time variant radio channel is obtained. The time evolving complex weights are as follows:

$$w_l(t) = g_l \cdot \exp(j2\pi\vartheta t), \quad l = 1, \dots, L \quad (3)$$

where ϑ is the Doppler frequency of the target LOS component. Then the emulated field at an arbitrary sample location u within the test area is (see Figure 1),

$$E(t, u) = \sum_{l=1}^L w_l(t) \cdot \alpha_{l,u} \quad (4)$$

where $\alpha_{l,u}$ is the transfer coefficient from the l -th OTA probe to the sample point u :

$$\alpha_{l,u} = L(d_{l,u}) \cdot \exp(-j\frac{2\pi}{\lambda}d_{l,u}) \quad (5)$$

$L(\cdot)$ is the pathloss term and $d_{l,u}$ is the distance from the l -th probe to the sample point u .

2) *NLOS component*: In the PFS technique, the goal is to approximate the NLOS component for any arbitrary PAS shape. The technique was proposed in [2], and is only outlined here.

Different clusters are modeled independently and each cluster is mapped to the probes, based on the cluster power angular spectrum (PAS) and the angular locations of the probes. The spatial correlation between channels obtained for different Rx locations is used as a figure of merit (FoM) to determine how accurately the spatial characteristics of the cluster at the Rx side (e.g. the impinging PAS shape of the cluster) are reproduced. The target spatial correlation is determined by the target PAS shape, while the emulated spatial correlation depends on the created discrete PAS shape, as omnidirectional DUT antenna patterns are generally assumed in multi-probe anechoic chamber study [3]. The discrete PAS shape is characterized by the discrete angular positions of the probes and the power weights. The optimal power weights for the probes can be obtained by minimizing the deviation between the target and emulated spatial correlation [2].

For the sake of simplicity, the channel coefficients associated with the n -th cluster and the s -th Tx antenna can be denoted as $\mathbf{h}(t)$, which is modeled by the ray based model [5]. Assume that the probe weights associated with the n -th cluster are denoted by $\mathbf{p} = [p_1, \dots, p_L]^T$ and hence the weighted transmitted channel coefficients associated with the n -th cluster can be represented as $[\sqrt{p_1} \cdot \hat{\mathbf{h}}_1(t), \dots, \sqrt{p_L} \cdot \hat{\mathbf{h}}_L(t)]^T$. Note that $\mathbf{h}(t)$ and $\hat{\mathbf{h}}_l(t)$ with $l \in [1, L]$ are independent and identically distributed complex sequences. The emulated channel coefficients on an arbitrary sample location u within the test area is,

$$\hat{\mathbf{h}}(t) = \sum_{l=1}^L \sqrt{p_l} \cdot \hat{\mathbf{h}}_l(t) \cdot \alpha_{l,u} \quad (6)$$

i.e., a summation of the contributions from each of the L probes. It is easy to check the emulated channel coefficients follow the target channel coefficients in terms of average power, temporal characteristics as well.

III. SIMULATION RESULTS

A. Simulation scenarios

Key parameters of the simulation setup is detailed in Table I. The target channel consists of a single LOS component with AoA = 22.5° (i.e. an angle exactly in the middle of two adjacent OTA probes in 8 uniform probe configuration) and a NLOS component, which is modeled by a single spatial cluster. Note that same delay is assumed for the LOS and NLOS component for the sake of simplicity, which is adopted in [5] as well.

B. Simulation results analysis

The objective of this section is to demonstrate how accurately the emulated Rician channel approach the target channel models in terms of field envelope distribution, K factor Doppler power spectrum and spatial correlation at the Rx side.

Table I
SIMULATION SETUPS

Probe setup	Details
	Eight uniformly distributed antennas on an OTA ring, as shown in Figure 1.
Channel models	<ul style="list-style-type: none"> Time samples $N_{ir} = 20000$ Samples per wavelength: 4 Center frequency: $f_c = 751\text{MHz}$ Direction of travel: 45° travel velocity: 30km/h LOS direction: 22.5° K factor: [-100dB, -10dB, 0dB, 10dB, 100dB] Channel model: The NLOS component is a single spatial cluster with AoA = 0° and AS = 35°

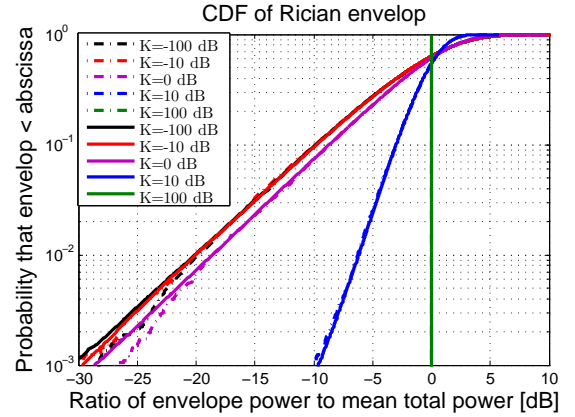


Figure 2. The Rice envelope cdf. The target curves are in solid lines and the emulated curves are in dot lines. Note that the curves for $K = -100\text{dB}$ and $K = -10\text{dB}$ lie on top of each other.

1) *CDF of the field envelope*: The cumulative density functions (CDFs) of the emulated Rician channels with different K factors are shown in Figure 2. The target CDFs are detailed in [8]. For a zero specular component ($K = -100\text{dB}$), the CDF distribution is Rayleigh. The CDF approaches Gaussian for a large specular component ($K = 10\text{dB}$). As explained in [8], the variance of the Gaussian distribution approaches 0 as the K factor approaches infinity, so the CDF plots approaches a delta function for $K = 100\text{dB}$. The CDF plots of the emulated channel generally follows the target very well. The deviations are mainly caused by the insufficient number of samples in the simulated channel.

2) *K factor*: Moment based estimation method of K factor is adopted [4]. The estimated K of the emulated channel matches very well with the target when K is larger than 0. The deviations when K is small are mainly due to the fact that the LOS component is difficult to detect accurately for small K , and estimation of the K factor is degraded [4], [9].

Table II
K FACTOR ESTIMATION.

Target K [dB]	-100	-10	0	10	100
Estimated K [dB]	-6.12	-20.14	0.18	10.06	99.96

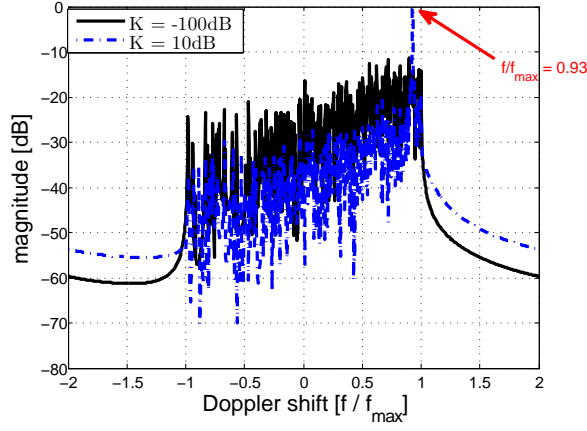


Figure 3. Doppler power spectra of the emulated channels with $K = -100\text{dB}$ and $K = 10\text{dB}$.

3) *Doppler power spectrum*: The Doppler power spectrum of the emulated channels with $K = -100\text{dB}$ and $K = 10\text{dB}$ are shown in Figure 3. The normalized Doppler frequency for the specular component is 0.93, which matches very well with the target normalized Doppler frequency $f_d^{los} = \cos(45^\circ - 22.5^\circ) = 0.92$. The Doppler spectra of the NLOS component for different K values have similar spiky shape, with different power levels.

4) *Spatial correlation at the Rx side*: Spatial correlation at the Rx side has been used as a measure to assess how accurately the emulated PAS, which is characterized by the probe weights and probe angular locations, match the target PAS. The estimated spatial correlation $\hat{\rho}_{ij}^{Rx}$ between the i -th and the j -th Rx antenna, both from the same 1st Tx antenna is:

$$\hat{\rho}_{ij}^{Rx} = \frac{\sum_{t=1}^{N_{ir}} [h_{1,i,1}(t) \cdot h_{1,j,1}^*(t)]}{\sqrt{\sum_{t=1}^{N_{ir}} |h_{1,i,1}(t)|^2 \cdot \sum_{t=1}^{N_{ir}} |h_{1,j,1}(t)|^2}} \quad (7)$$

The target spatial correlation can be calculated, as detailed in [8]:

$$\rho_{ij} = \frac{\int_{-\pi}^{\pi} G_i(\phi) G_j^*(\phi) p(\phi) d\phi}{\sqrt{\int_{-\pi}^{\pi} p(\phi) |G_i(\phi)|^2 d\phi} \sqrt{\int_{-\pi}^{\pi} p(\phi) |G_j(\phi)|^2 d\phi}}, \quad (8)$$

where G_i and G_j are the complex radiation patterns of antenna element i and j , respectively, with a common phase center. $p(\phi)$ is the PAS which satisfy $\int_{-\pi}^{\pi} p(\phi) d\phi = 1$ and it is the combination of the LOS ray and the NLOS PAS.

A uniform linear array (ULA) consists of 21 ideal dipoles with array broadsight 0 degrees are selected as the Rx antennas. The coupling between antenna elements are not considered in this study. The spatial correlations of the target and emulated channels with different K values are shown in Figure 4. The spatial correlation depends highly on the K factors, with correlation 1 among all the antenna elements for a pure LOS ($K = 100\text{dB}$). The emulated spatial correlation follows the target curve well up to 0.7λ and deviates after that. This is due to the fact that with eight probes, the created test area size, inside which the channel can be accurately modeled,

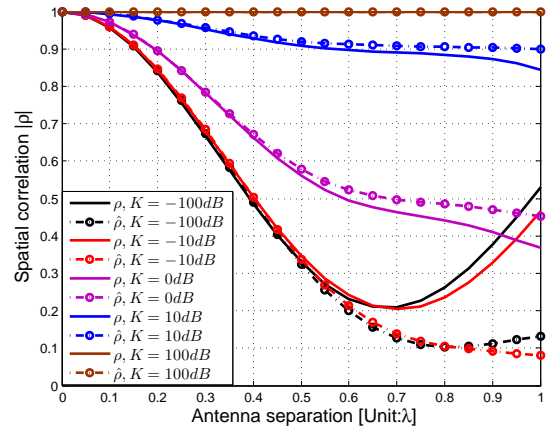


Figure 4. Spatial correlations of the target and emulated channels with different K values.

is limited. Similar conclusions are drawn for Rayleigh fading channel models [2].

IV. CONCLUSION

A method to create Rician fading channel model with a LOS component with arbitrary polarization and direction is proposed. Both phase and amplitude calibration are required to model the LOS component. Simulation results show that the field envelope distribution, K factor, and Doppler spectrum of the emulated channels match well with the target. The emulated spatial correlation at the Rx side follows the target well up to 0.7λ and deviates after that due to the fact that the test area size, inside which the spatial characteristics of the channel are accurately modeled, is limited with eight probes.

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